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Original paper

Evaluation of ultrasonic sensor for variable-rate spray applications

Hong Y. Jeon[a,*], Heping Zhu[a], Richard Derksen[a], Edal Ozkan[b], Charles Krause[a]

[a] USDA-ARS Application Technology Research Unit, 1680 Madison Ave., Wooster, OH 44691, USA
[b] Ohio State University, 226 Agricultural Engineering Bldg., 590 Woody Hayes Dr., Columbus, OH 43210, USA

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ABSTRACT

Automatic variable-rate sprayers require accurate measurement of canopy size. An estimate of canopy size is made by measuring the distance to the canopy at several elevations above the ground; an ultrasonic sensor was used to determine canopy distance in this study. It is sometimes necessary to conduct spray operations during harsh operating conditions. In this study ultrasonic sensors were subjected to simulated environmental and operating conditions to determine their durability and accuracy. Conditions tested included exposure to extended cold, outdoor temperatures, cross winds, temperature change, dust clouds, travel speeds and spray cloud effects. The root mean square (RMS) error in a series of measurements of the distance to a simulated plant canopy was used to test for significant difference among treatments. After exposure to outdoor cold conditions for 4 months, the RMS error in distance measured by the ultrasonic sensor increased from 3.31 to 3.55 cm, which was not statistically significant. Neither the presence of dust cloud nor the changes in cross-wind speeds over a range from 1.5–7.5 m/s had significant effects on the mean RMS errors. Varying sensor travel speed from 0.8 to 3.0 m/s had no significant influence on sensor detection distances. Increasing ambient temperature from 16.7 to 41.6 °C reduced the detection distance by 5.0 cm. The physical location of the spray nozzle with respect to the ultrasonic sensor had a significant effect on mean RMS errors. The mean RMS errors of sensor distance measurements ranged from 2.3 to 83.0 cm. The RMS errors could be reduced to acceptable values by proper controlling the sensor/spray nozzles spacing on a sprayer. In addition, multiple-synchronized sensors were tested for their measurement stability and accuracy (due to possible cross-talk errors) when mounted on a prototype sprayer. It was found that isolating the pathway of the ultrasonic wave of each sensor reduced detecting interference between sensors during multiple sensor operation. Test methods presented herein may be useful in the design of standardized testing protocols for field use distance sensors.

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1. Introduction

Tree liners are young trees grown in nurseries prior to being transplanted to fields or containers where they continue growing into larger, market-ready shade trees. The liners are usually one to three years old, and grow very fast. For example, red maple, Acer rubrum (*Autumn Blaze*) liners can grow more than 1 m during a single growing season (Mathers et al., 2005). Demand for tree liners by consumers is very strong. The state of Ohio alone annually purchases approximately $14 million worth of liners from other states (Pollock, 2005). Pesticide application plays an important role in maintaining the quality of tree liners by protecting them from potential biological damage. Applicators are supposed to adjust the spray volume as the canopy size changes during the growing season. However, variability in growth rates among liners produces a range of sizes in the field. Thus field adjustment to achieve a reasonable match between sprayer application rate and canopy size is impractical for current liner sprayers. In addition, operators are unable to halt spraying during gaps between trees in a row. Thus, a sprayer that automatically adjusts spray volume based on sensed canopy size is anticipated to achieve two goals: to maximize efficiency by applying the optimum amount of spray to target trees and controlling spray between trees.

Measuring canopy size is a challenge due to the complicated growth structures and irregular shapes of trees. Various remote sensing techniques have been investigated to achieve this goal. For example, light interception and aerial stereoscopic imaging techniques have been adapted to estimate tree canopy size (Meron et al., 2000). Satellite images have also been used to estimate canopy volume of trees in forest (Mäkelä and Pekkarinen, 2004; Carreiras et al., 2006; Mõttus et al., 2006; Le Maire et al., 2008).

However, the scale of these remote sensing techniques is relatively large and consequently, the sensing resolution may be insufficient for a real-time variable rate application in a liner production field. In addition, remote sensing techniques typically have

* Corresponding author. Tel.: +1 330 263 3871; fax: +1 330 263 3953.
E-mail addresses: hongyoung.jeon@ars.usda.gov, redyoung@gmail.com (H.Y. Jeon).

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a chronological gap between detection and application, resulting in application errors. To reduce this problem, a LIDAR (Light Detection and Ranging) system or a laser scanner has been used to measure canopy volume. Promising results were reported for using this system in which measured canopy volume was close to manually measured volume (Wei and Salyani, 2005; Lee and Ehsani, 2008; Rosell Polo et al., 2009). Unfortunately, the narrow row spacing in a liner field may restrict LIDAR from being used on variable rate liner sprayers. It is also a relatively expensive sensor ($2000–6000). Furthermore, a typical tree liner sprayer treats multiple rows at a time. Each liner row would require an individual LIDAR system to measure its tree canopy variation. Thus controlling a variable-rate application sprayer would require several LIDAR systems. This would increase the application cost to an impractical level.

Ultrasonic sensors that are affordable, relatively robust during outdoor conditions, and capable of estimating the canopy volume of trees satisfactorily have been used by several researchers (Giles et al., 1988; Tumbo et al., 2002; Zaman and Salyani, 2004). These studies were focused on sensing canopy volume of fully grown orchard trees with relatively large spacing between rows that provided sufficiently clear line-of-sight for the sensors. Their field conditions were different from a typical tree liner field: typical liner spacing is from 1.22 to 1.52 m. Furthermore, during a growing season, row spacing became even narrower due to canopy development. Therefore, canopy detection methodology suitable for an orchard may be inappropriate for liner applications.

While ultrasonic sensors have been used in earlier studies for detecting canopy size, sensor performance has not been well examined under field conditions. In addition, liner field application presents unique challenges to a canopy sensing system, i.e., relatively dense tree liner arrangement, rapid canopy size and color changes, and limited working space between rows for the sensing system (Fig. 1). Ultrasonic sensors may overcome these challenges due to their small size, robust sensing mechanism against color variation in targets, and uni-directional sensing line-of-sight.

However, although the performance of ultrasonic sensors have been presented in the literature, questions regarding the sensor's performance under harsh field, spray application, and multiple sensor operating conditions still remain. For example, Zaman and Salyani (2004) reported canopy density and ground speed influence on tree canopy detection when using ultrasonic sensors. Although they reported on ground speed and foliage density effects on sensor measurements, they examined the sensor performance under limited field conditions and for relatively slow travel speeds (1.6–4.7 km/h) compared to typical liner applications. In addition, Giles et al. (1988) reported that traveling at the speed of 2–6 km/h had no significant effects on the capability of their ultrasonic sensors to detect tree canopy volume. The performance of multiple sensor operation should be evaluated while they are operating simultaneously because measuring tree canopy requires multiple sensors (Giles et al., 1988; Tumbo et al., 2002; Zaman and Salyani, 2004; Solanelles et al., 2006; Gil et al., 2007). Although multiple ultrasonic sensors were used in one system to detect tree canopy, sequentially triggered sensors were used in their study to prevent interference between adjacent sensors (Tumbo et al., 2002; Zaman and Salyani, 2004). However, sequentially triggering sensors are not a feasible option for liner application due to rapid changes of liner canopy sizes. Consequently, the reported results were not sufficient to conclude that an ultrasonic sensor was feasible for tree liner field spray application.

Fig. 1. Spray application in a typical tree liner field.

Therefore, the work presented here was to test an ultrasonic sensor for field sprayers, particularly in tree liner application, with a possible contribution toward developing a testing protocol for outdoor-use ultrasonic sensors. A wide range of parameters were evaluated in this study to determine sensor performance under a wide range of field conditions. Parameters studied included: cold weather exposure, cross-wind, dust environment, air temperature, spray cloud and multiple sensor operation. Therefore, the overall objective of this research was to verify the feasibility of using an ultrasonic sensor for tree liner field sprayers. The specific objectives were:

(1) to test the durability and measurement stability of an ultrasonic sensor under laboratory simulated, potential field spray application conditions and
(2) to determine the optimum sensor implementation strategy for a variable-rate tree liner sprayer.

2. Materials and methods

2.1. Ultrasound sensor

An outdoor-use, water proof ultrasound sensor (LV-MaxSonar-WR1, Maxbotix Inc, Brainerd, MN, USA) was used in this research. The sensor was rated as IP (ingress protection) 67 which refers to dust tight (6) and 1-m water immersion protection (7) (CENELEC, 2000). The sensing resolution was 3.82 mV/cm with an approximate beam angle of 10°. The sensor body was constructed with a pipe connector and cable grip to protect the sensor under the outdoor conditions (Fig. 2).

Although other ultrasonic sensors, such as the one currently used on a Durand Wayland (DW) orchard sprayer (LaGrange, GA, USA) are available, we selected the IP67 rated sensor because of its fast detecting frequency (20 Hz), necessary for higher travel speeds, and the acceptable minimum detecting range (30.48 cm) for tree liner application. In addition, due to sensing signal interference, the DW sensors were unable to simultaneously detect canopy range, which is a critical issue for dense liner field conditions.

2.2. Data acquisition system

To acquire data from sensors, a custom-designed data acquisition system was built with a peripheral interface controller (PIC) (PIC18F4523, Microchip technology Inc., Chandler, AZ, USA). The PIC triggered the sensor and received analog signals from the sensor. By using the embedded 12-bit analog-to-digital (AD) converter module of the PIC, the signal was converted to a discrete digital number ranging from 1 to 4096. The data acquisition and sensor system resolution in measuring distance was 0.32 cm. After the AD conversion, the digital information was sent to a laptop computer via serial communication. To acquire the data, a user interface was written using Visual Basic.NET (Microsoft Co. Ltd, Richmond, WA,

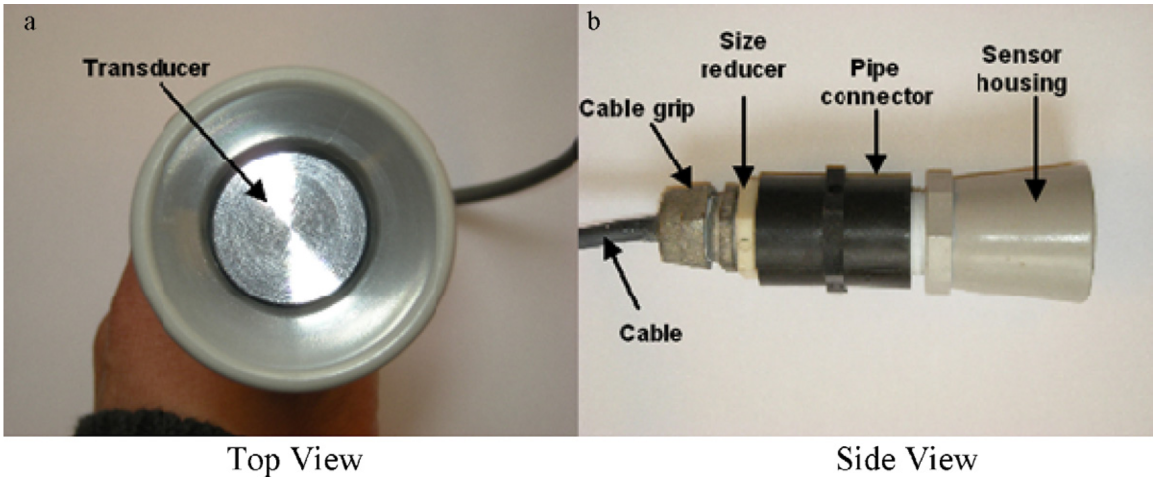

Fig. 2. Ultrasonic sensor with protection components for outdoor conditions.

USA) to examine sensing results and to save data in a text file at various sampling rates.

2.3. Ultrasonic sensor testing under potential field spray application conditions

Durability is one of the major factors required for sprayer quality, thus, the sensors for an automated sprayer must be tested under outdoor application conditions. In addition to durability, ultrasonic sensors must produce accurate tree canopy measurements over the entire range of environmental and application conditions that the sensor might encounter during spray and non-spray seasons. The sensor was evaluated under the following six conditions: extended cold weather exposure, cross-wind speed, dust cloud, travel speed, air temperature, and spray cloud. These are the minimum factors that the sensor is likely to confront under field application conditions. During the course of the test, identical artificial plants were used instead of real plants because artificial plants had constant canopy structures during the long duration of the tests (Fig. 3).

2.3.1. Cold weather exposure

To evaluate the sensor performance and durability after exposure to cold weather conditions, the IP67 sensor was mounted on a weather station for 40 days between March 4 and April 13, 2009. The ambient temperature and precipitation were recorded by the weather station and are illustrated in Fig. 4. The root mean square (RMS) errors of the detecting distance for a 46-cm tall artificial plant was evaluated before and after the sensor was exposed outside conditions for 40 days. The distance between the sensor and the plants was 167.64 cm. Plant detecting test was replicated three times, and detecting data were collected for 5 min, at a sampling rate of 10 Hz, for each replication. The differences in RMS errors of the IP67 sensor measurements after the exposure to cold weather were subjected to analysis of variance (ANOVA) at the significance level of 0.5 with MS-Excel software (Microsoft Co. Ltd, Redmond, WA, USA) by using completely randomized experimental design (CRED).

Fig. 3. Artificial plants for testing ultrasonic sensors.

2.3.2. Cross-wind test

A wind tunnel was used to evaluate the sensor accuracy and measurement stability under windy conditions. The tunnel simulated laminar wind flow at different speeds passing through the line-of-sight of the sensor.

The IP67 sensor was mounted perpendicular to the airflow at 73.7 cm above the tunnel floor; it measured the distance to the tunnel floor. An air velocity meter (Model 8386A, TSI Inc., Shoreview, MN, USA) was used to measure the wind speed (Fig. 5) approximately 66 cm downstream from the sensor. The range of wind speeds tested was from 1.5 to 7.5 m/s at 1.5 m/s increments. This range represented conditions that could be defined as ‘ideal’ to ‘caution advised’ spray conditions (Deveau, 2009). The ultrasonic sensor output data were acquired for 5 min at a sampling rate of 10 Hz with 3 replications for each wind speed. The wind impact on RMS errors of the IP67 sensor detection was examined by ANOVA at the significant level of 0.5 with CRED.

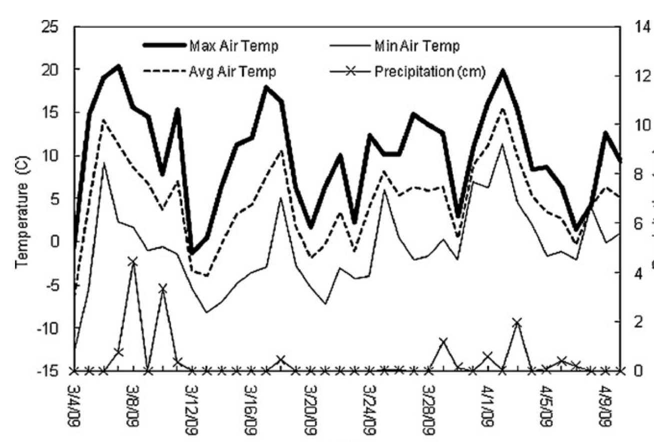

Fig. 4. Ambient temperature and precipitation during the outdoor winter durability test of the sensor.

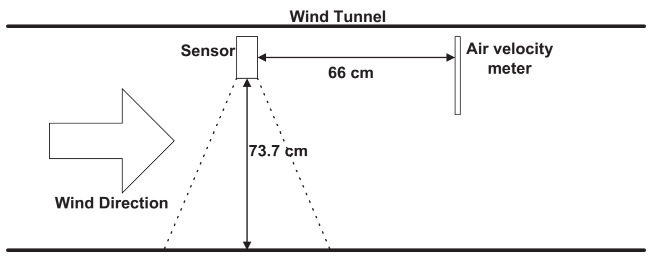

Fig. 5. Wind tunnel setup for the sensor stability test under windy conditions.

2.3.3. Dust cloud test

To evaluate sensor performance, the RMS errors of target distance measured by the IP67 sensor were determined with and without a dust cloud in the sensor's line-of-sight. The sensor was mounted at the top of a box (74.0 cm (width: W) by 62.9 cm (length: L) by 95.3 cm (height: H)), with a funnel to discharge dust into the sensing area placed 17.8 cm away from the sensor (Fig. 6). The distance from the sensor and the ground was measured. Dust was prepared by filtering ground soil through a 234-μm screen; 570 g of dust was poured via the funnel during 50 s. Fan-blown air carried the dust particles to the line-of-the-sight of the sensor at a velocity of 3.6 m/s. The sensor output was collected for 50 s, synchronized with the introduction of the dust, at a sampling rate of 10 Hz, with three replications. The RMS errors of the sensor measurements were examined through ANOVA. A CRED was assumed for ANOVA.

2.3.4. Travel speed

The RMS error of the sensor's detection results was used to evaluate its detection accuracy and measurement stability over a range of travel speeds. A custom-designed linear track was used to simulate sprayer travel (Fig. 7). The sensor was mounted on the track and driven by a stepper motor. The detecting targets were 40-cm high and 106.7-cm long artificial plants, placed 81.9 cm under the track.

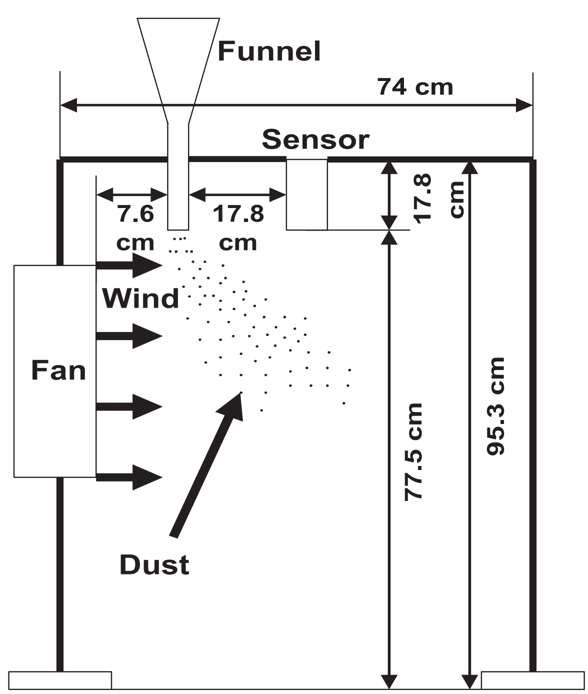

Fig. 6. Experimental setup for the sensor stability test under dust conditions.

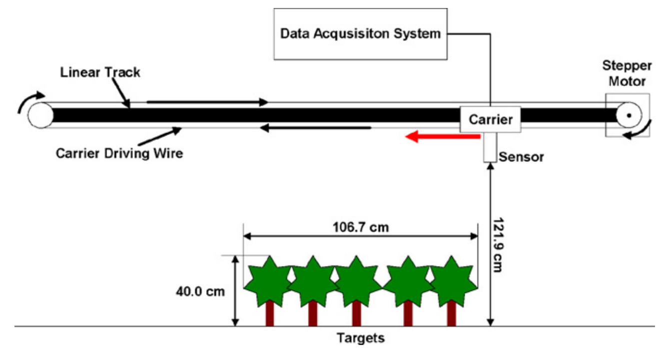

Fig. 7. Experimental setup to test the sensor stability at various travel speeds.

The sensor travel speed ranged from 0.76 m/s to 3.24 m/s, measured with a radar gun (Railmaster-VP, Decatur Electronics Inc., Decatur, IL, USA). The detection data provided by the sensors were assigned into five travel speed groups: 0.76–0.93 m/s, 1.33–1.60 m/s, 1.78–2.13 m/s, 2.36–2.67 m/s, and 2.71–3.24 m/s corresponding to average speeds of 0.8, 1.5, 2.0, 2.5 and 3.0 m/s, respectively. While the sensor was traveling, the data acquisition system collected the target distances for 5 s at the sampling rate of 20 Hz. Between 8 and 10 trials were made for each speed group. RMS errors of the sensor measurements on each speed, including a stationary position trial, were calculated, and their differences were computed by ANOVA analysis with CRED at the significance level of 0.5.

2.3.5. Air temperature

An insulated chamber (0.91 cm (W) × 0.91 cm (L) × 1.22 cm (H)) with 2.5 cm thick-foam was built to maintain steady and uniform air temperature for testing the air temperature influence on sensor measurements.

The chamber temperature was measured at three positions using T-type thermocouples while the chamber temperature was controlled by discharging heated air into the chamber. The thermocouples were installed in the chamber at the heights of 2.5, 70 and 113 cm from the base. The ultrasonic sensor was mounted at the top of the chamber at the height of 125 cm from the base, and measured the distance to the chamber base while the air temperature was controlled. The temperature and sensor measurements were recorded continuously by a data logger (CR3000, Campbell Scientific Inc., Logan, UT, USA) at a sampling rate of 1 Hz. Sensing distance and temperature were measured for 8 h.

The sensing data were filtered by eliminating data points when the differences between the mean and three measured temperatures were greater than 1 °C. Therefore, detected distance data were used only when the air temperatures within the chamber was homogeneous. The range of the average air temperature in the chamber for the test was from 16.7 to 41.6 °C.

2.3.6. Spray cloud

The RMS errors of the sensor distance measurements were used to examine the measurement stability of the sensor while spray clouds were discharged from a spray nozzle (XR11003, Teejet Co., Wheaton, IL, USA). The sensor was mounted at the top of an upside-down 2.13 m × 2 m L-shape frame (Fig. 8). To develop a sensor installation strategy with respect to a spray nozzle for the desired detection stability and accuracy of the sensor, configurations of horizontal (HD), vertical (VD), and longitudinal distances (LD) between the sensor and the nozzle (sensor–nozzle configuration) were tested with the test frame (Table 1).

For each sensor–nozzle configuration, the nozzle discharged spray clouds perpendicular to the detecting area of the sensor.

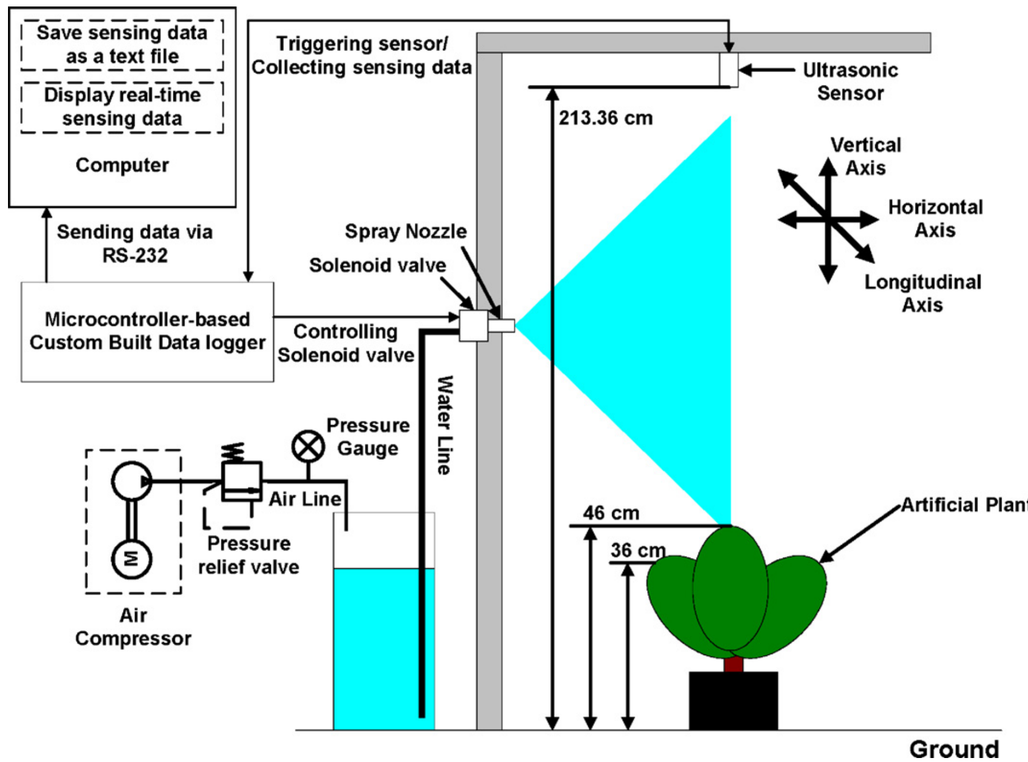

Fig. 8. Experiment setup to test the sensor stability with the spray clouds.

While the nozzle was spraying water through detection area, the sensor continuously measured the distance to a 46-cm tall artificial plant. The nozzle was operated at 207, 276, 345 and 414 kPa, and each sensor–nozzle configuration was examined under all operating pressures. The operating pressure was carefully controlled by pressurized air. Spray nozzle operation was controlled by a solenoid valve (Capstan Ag Systems, Inc., Topeka, KS, USA) coupled with an N-channel power MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor, RFP12N10L, Fairchild, South Portland, Maine, USA). The PIC in the data acquisition system triggered the valve via a logic signal to synchronize the action of the data acquisition and nozzle spraying.

Sensor output data were collected for 5 min at the sampling rate of 10 Hz, and data collection was replicated three times for each sensor–nozzle configuration and operating pressure. From the collected data, RMS errors of the sensor measurements were calculated, and the errors were subjected to ANOVA to identify the differences in the RMS errors on spray nozzle operating pressures, LD, HD and VD at the significant level of 0.5 by SAS (Version 9.1, Cary, NC, USA). SAS was used for ANOVA due to data size and volume, and a CRED was used for ANOVA.

2.3.7. Multiple sensor operation

Five ultrasonic sensors were mounted on a 2.1 m bar with a sensor spacing of 0.30 m to identify interference issues between sensors and to examine sensor accuracy in detecting canopy volume. Five sensors were controlled and synchronized by a custom designed microcontroller to simultaneously detect targets at each position.

Interference between sensors was identified (Zaman, and Salyani, 2004) as resulting from variation in reflected sound wave path lengths due to angled plant surfaces. To reduce this problem, an interference prevention cylinder was designed and mounted on the sensor's enclosure (Fig. 9) to isolate the pathway for the ultrasonic wave from each IP67 sensor, and to prevent interference between sensors while sensing angled surfaces. The inside cylinder diameter was approximately 7.62 cm, and the cover extends approximately 11.43 cm from the transducer. A 2.54-cm thick sound absorbing form was glued around the inside wall of the cylinder, thus approximately 2.54-cm diameter circle opening was available to transmit and receive the sound wave.

Two experiments were carried out to test synchronized multiple sensor operation and its detection accuracy. A flat wood panel (185.4 cm (H) × 24.8 cm (W)) was placed at specific distances (30.5, 38.1, 45.7, 53.3, 61.0 and 68.6 cm) from the sensors to examine detecting accuracy. In addition, artificial canopies mounted in elliptical, diamond and diagonal shapes were created to test the sensors. While the sensors were detecting targets, detection results were acquired by a computer via RS-232, and the acquired data were stored in a text file. Each test replicated three times, and RMS errors of the sensing results were computed to evaluate the detection accuracy.

Table 1
Sensor–nozzle configurations for the test.

Configuration	Distance (m)
Horizontal distance (HD)	0.30 and 0.61
Longitudinal distance (LD)	0[a], 0.15, 0.3, 0.45 and 0.61
Vertical distance (VD)	0.3, 0.61, 0.91 and 1.22

[a] 0 means the sensor and nozzle were placed in a longitudinally equal line.

3. Results and discussion

3.1. Cold weather exposure

There was no change in function or accuracy of the ultrasonic sensor after it was exposed to outdoor cold weather conditions for 40 days. The RMS errors of the measurements ranged from 2.15 to 4.06 cm with the mean of 3.31 cm, and 2.71 to 4.94 cm with the mean of 3.55 cm for before and after the exposure, respec-

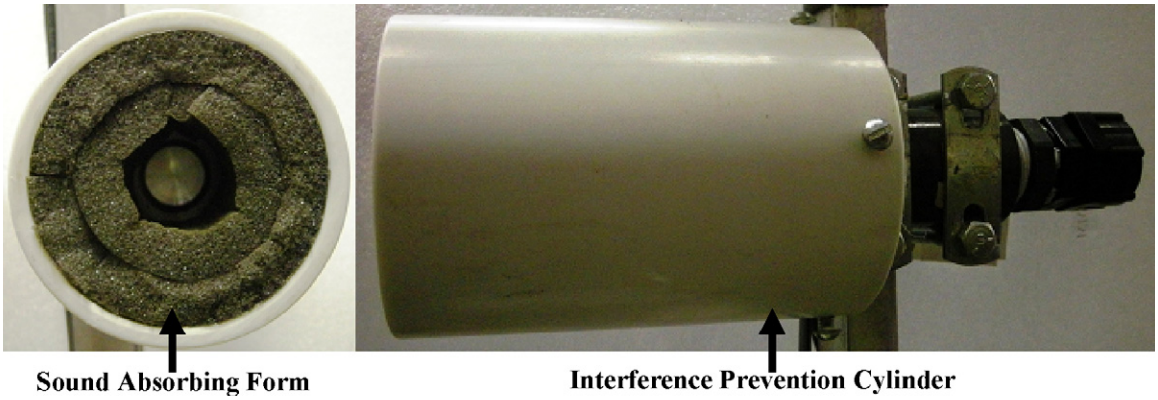

Fig. 9. Ultrasonic sensor with an interference prevention cylinder.

Table 2
RMS errors of the sensor detecting distances before and after 40-day exposure under outdoor winter conditions.

	Before exposure	After exposure
RMS error (cm)[a]	2.15	2.71
	4.06	3.00
	3.72	4.94
RMS error mean (cm)	3.31	3.55
SD[b]	1.02	1.21

[a] RMS error: root mean square error between actual and detected distances.
[b] SD: standard deviation.

tively (Table 2). The increase of the mean RMS error was 7.3% after the exposure; however, ANOVA results indicated that the increase was not significant ($P > 0.05$). RMS errors from the test had an LSD (least significant difference) value of 2.54 cm ($P < 0.05$). The insignificant difference in the RMS errors implies that the components and enclosure of the sensor provided sufficient durability and performance after extended outdoor storage in cold weather conditions.

3.2. Wind test

The RMS error of the sensor measurements ranged from 1.11 to 1.34 cm (Table 3) across all wind speed conditions evaluated. No significant difference between RMS errors within the wind velocity range from 1.5 to 7.5 m/s was found ($P > 0.05$). The results indicated that the accuracy and function of the sensor were not influenced by the tested wind speed range. Thus, the measurement stability of the sensor was reasonable under the windy conditions. An LSD value for RMS errors was 0.07 cm ($P < 0.05$).

3.3. Dust cloud test

Measurement results taken to determine the stability of sensors under dusty condition revealed that the sensor had sufficient detection stability under dusty conditions although the transducer and the line-of-sight of the sensor were covered by dust. The RMS error of the sensor measurements ranged from 4.99 to 8.46 cm with the mean of 6.2 cm for the target which was 77.5 cm away from the sensor. On the other hand, the RMS errors without dust on the line-of-sight of the sensor ranged from 2.71 to 4.94 cm with the mean of 3.55 cm. Differences were not significant ($P > 0.05$, LSD value = 3.72 cm ($P < 0.05$)). Therefore, the sensor had reasonable measurement stability and accuracy under dusty conditions that exceeding conditions likely to be observed during field applications.

Table 3
RMS error of the sensor detecting distances under various wind speed conditions.

	Wind speed (m/s)				
	1.5	3.0	4.5	6.0	7.5
RMS error[a] (cm)	1.27	1.34	1.16	1.16	1.11
	1.27	1.32	1.17	1.19	1.41
	1.30	1.30	1.22	1.16	1.37
RMS mean	1.28	1.32	1.18	1.17	1.30
SD[b]	0.02	0.02	0.03	0.02	0.2

[a] RMS error: root mean square error between actual and measured distances.
[b] SD: standard deviation of the RMS errors.

3.4. Travel speed

Mean RMS errors of the sensor measurements ranged from 10.1 to 19.4 cm while detecting targets 81.9-cm away from the sensor at average traveling speeds of 0.8–3.0 m/s (Table 4). Relatively large mean RMS error (19.4 cm) was observed at the low speed (0.8 m/s), and the lowest mean RMS error (10.1 cm) occurred at the 2.0 m/s travel speed. Similar to the results reported by Giles et al. (1988) and Zaman and Salyani (2004), our test results indicated that no significant differences existed in RMS errors of detection results for tested travel speed range ($P > 0.05$). An LSD value of the RMS error data was 5.57 cm ($P < 0.05$).

In our test, the sensor generally showed acceptable performances for detecting the artificial canopy within the speed range. Random distance-detecting errors were observed during the test. Zaman and Salyani (2004) reported that sensing variation along the traveling speeds might be caused from target scanning frequency and canopy variability. However, our detecting error might have resulted from the acoustic wave bouncing between angled leaves until the wave returned to the sensor's receiver (multi-return path effects) due to leaf orientations (McKerrow and Neil, 2001).

A filtering process, i.e., using a derivative between two adjacent sensing points was suggested to increase detecting accuracy by eliminating the low frequency abnormal amplitude errors (1.0–5.6% of collected data). This hypothesis was evaluated by applying a manual derivative filter to detection results. The filtering results indicated that the range of RMS errors was reduced from

Table 4
Mean RMS error for the 81.9 cm detection distance under various travel speed conditions.

	Average speed (m/s)				
	0.8	1.5	2.0	2.5	3.0
Mean RMS error (cm)[a]	19.4	12.7	10.1	12.32	10.8
SD[b]	11.2	14.3	13.3	13.4	8.0
Sensing error (%)	5.0	1.6	1.0	3.2	5.6

[a] RMS error: root mean square error between actual and sensing distances.
[b] SD: standard deviation of the RMS errors.

Table 5
Detected distances of targets 125 cm away from the sensor under the ambient temperature ranging from 16.7 to 41.6 °C.

	Air temperature range (°C)		
	Below 19	19–35	Above 35
Average detected distance (cm)	125.32	122.83	120.36
Coefficient of variation (%)	0.34	0.22	0.17
Measurement change (%)	–	−2	−4
RMS error (cm)	0.5 (0.4)[a]	2.2 (1.8)	4.6 (3.7)

[a] Figures in parentheses are the percentage of RMS error to the 125 cm target distance.

between 10.1 (8.3% of detecting distance) and 19.4 cm (15.9%) to between 6.4 (5.2%) and 7.9 cm (6.5%).

3.5. Air temperatures

Within the air temperature range from 16.7 to 41.6 °C, two distinctive changes in detection distances were identified as the chamber temperature increased: a change in detection distances occurred between the air temperatures of 18 and 19 °C, and another change occurred as the air temperature increased from 34 to 35 °C. The average detection distance decreased by approximately 2.5 cm (2% of the sensing distance of 125 cm) for each change. The sensor showed 0.5 cm, 2.2 cm and 4.6 cm of RMS errors when the air temperature was below 19 °C, between 19 and 35 °C and above 35 °C, respectively (Table 5). The potential maximum change in average sensing distance within the tested air temperature range was 5.0 cm.

The change in the speed of sound between two air temperatures is directly proportional to the square root of the ratio of the two temperatures in kelvin (Bohn, 1988). Our test results showed the reduction of the average detection by 4% while the potential speed of sound increased by 4.21% for the temperature range tested (19–35 °C). This disagreement of approximately 0.21% could be caused by the data sampling method which allowed for ±1 °C temperature variation in chamber air temperature from average temperature.

3.6. Spray clouds

The range of mean RMS errors varied from 2.3 cm to 83.0 cm under the effect of spray clouds when the detection distance of the IP67 sensor was 167.6 cm (Table 6 and Fig. 8). It was evident that vertical distance (VD), horizontal distance (HD), and longitudinal distance (LD) configurations between the sensor and nozzle influenced measurement accuracy. For example, increasing VD had significant effects on RMS errors ($P < 0.05$). The significantly reduced RMS errors at large VD distances (spray nozzle farther from the sensor) might be due to the reduced amount of spray that reached the sensor as VD increased, i.e., spray liquid deposits on the transducer were reduced. The LSD value for the RMS error data was 4.57 cm.

Increasing HD also had significant effects on RMS errors ($P < 0.05$). Although increasing HD improved the RMS error relatively little, the significant influence was possible because droplet trajectory and travel distance to the transducer changed by the interaction of the spray pattern and HD. An LSD value of 3.30 cm was identified for the RMS error data ($P < 0.05$). Increasing LD also

Table 6
Means of RMS errors (cm) collected from the sensor and nozzle configurations with nozzle operating pressures ranging from 207 to 414 kPa.

Vertical distance[a] (m)	Horizontal distance[a] (m)		Longitudinal distance[a] (m)				
			0	0.15	0.30	0.45	0.61
0.30	0.30	Max.	119.4	74.7	10.3	9.2	9.1
		Min.	42.61	2.0	1.4	2.5	3.4
		Mean	83.0	12.1	5.3	4.7	6.6
		SD[b]	26.6	12.7	1.0	2.2	1.7
	0.61	Max.	85.4	80.2	9.5	8.3	8.0
		Min.	10.3	6.9	2.5	0.6	2.3
		Mean	27.9	14.1	5.1	4.2	4.2
		SD	11.4	17.3	2.8	3.0	3.1
0.61	0.30	Max.	101.6	30.0	9.0	8.6	8.8
		Min.	32.2	2.4	1.1	2.2	1.4
		Mean	77.0	7.3	4.2	6.2	4.5
		SD	10.5	4.4	1.5	1.9	2.4
	0.61	Max.	64.6	51.6	7.4	7.1	9.5
		Min.	3.0	4.3	2.3	0.0	2.2
		Mean	12.0	11.3	4.5	4.1	3.2
		SD	11.5	8.8	2.5	2.6	2.7
0.91	0.30	Max.	12.1	9.0	10.4	8.9	8.4
		Min.	2.1	3.5	1.6	0.0	1.8
		Mean	6.1	6.8	5.5	4.8	5.2
		SD	0.7	1.7	2.2	2.9	2.1
	0.61	Max.	37.6	41.0	8.0	8.1	8.7
		Min.	3.8	2.6	2.9	0.7	2.5
		Mean	10.4	13.4	4.5	3.9	4.5
		SD	6.6	10.6	1.9	2.2	3.0
1.22	0.30	Max.	12.3	8.9	9.4	9.5	8.1
		Min.	2.1	2.5	1.8	0.0	2.2
		Mean	8.2	5.6	5.5	6.0	4.4
		SD	2.4	0.7	1.3	2.6	1.0
	0.61	Max.	6.5	12.6	6.2	10.3	10.0
		Min.	1.4	4.4	1.3	0.0	1.17
		Mean	3.1	6.5	2.3	3.6	3.3
		SD	1.9	4.4	1.4	2.6	1.8

[a] Distance is between the sensor and nozzle.
[b] SD: standard deviation of the RMS errors.

Table 7
Mean RMS errors (cm) of distance measurements from five sensors while detecting wood panel targets at 30.5, 38.1, 45.7, 53.3, 61.0 and 68.6 cm away from the sensors.

Target detecting distance (cm)	Sensor 1[a]	Sensor 2	Sensor 3	Sensor 4	Sensor 5
30.5	0.26	0.31	0.27	0.35	0.35
38.1	4.40	4.84	4.80	4.30	4.87
45.7	5.03	6.13	5.03	5.01	5.00
53.3	4.64	2.48	2.54	4.58	4.92
61.0	5.02	4.88	6.91	6.28	5.01
68.6	4.66	4.78	6.74	4.69	4.96

[a] Sensor 1 was mounted approximately 30.5 cm above from the ground and the spacing between sensors was 30.5 cm.

produced significant effects in the RMS errors ($P < 0.05$). The RMS errors might be significantly improved by increasing LD because greater LD between nozzles and sensors resulted in less spray liquid deposition on the sensors. An LSD value of 4.59 cm was identified for the RMS errors. The effect of spray nozzle operating pressure on RMS errors ($P > 0.05$) was not significant. An LSD value of 4.78 cm was estimated ($P < 0.05$). Therefore, spray droplet size did not significantly effect RMS errors, for the range of droplet sizes tested here.

From the results shown, it is obvious that improved detection accuracy can be achieved by positioning the spray nozzles far enough from the ultrasonic sensors to prevent spray droplets from settling on the transducer. An example of spray application error due to canopy size measurement errors can be computed by assuming a typical spray scenario. Assumed application conditions are: trapezoid canopy shape within the sensing area, travel speed range of 0.45–1.34 m/s and an application rate of 93.8 mL/m^3 (Anonymous, 2009). Using mean RMS errors from appropriate sensor–nozzle configurations (mean RMS error: 4.2 cm (HD: 0.30 m, VD: 0.61 m and LD: 0.30 m), and 4.5 cm (HD: 0.61 m, VD: 0.61 m and LD: 0.30 m)), variations in the canopy size sensing results and their influence in application rates can be estimated. For example, the RMS errors from the selected configurations may result in over application of 26.8–92.0 μL of spray mixtures per nozzle for a canopy detecting interval of 50 ms, and sensor spacing of 30.48 cm. The variation in spray delivery resulting from inaccurate target detection may range from 5.3 to 7.9% for each sensing cycle, thus, reasonable detection accuracy can be achieved from sensor-controlled spray.

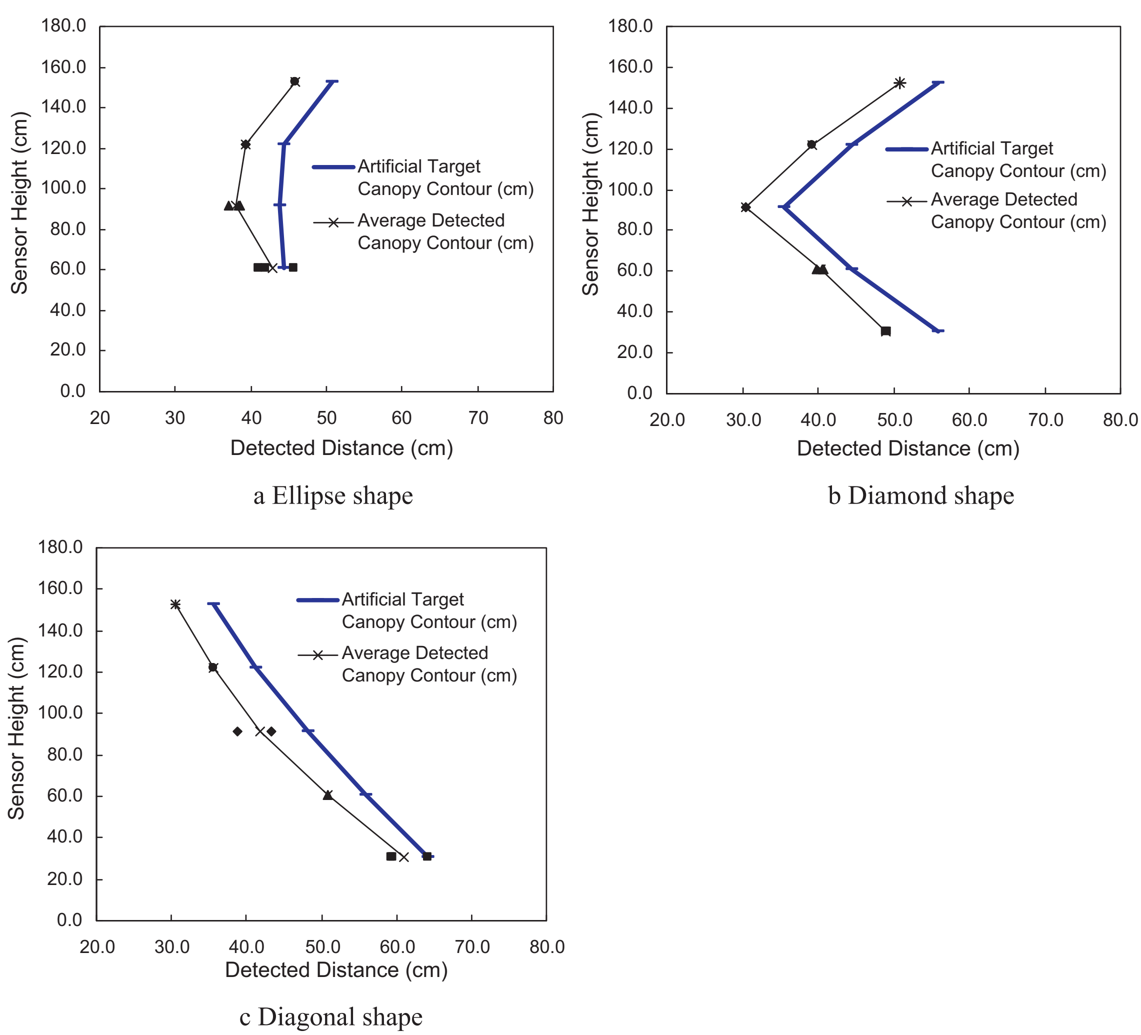

Fig. 10. Detection results of artificial canopy shapes by vertically installed sensors.

3.7. Multiple sensor operation

Our preliminary studies confirmed earlier results (Zaman and Salyani, 2004) that multiple ultrasonic sensors, mounted at a 30.48-cm spacing, produce interference, even when using an artificial canopy. Therefore the interference prevention cylinders were used for these measurements.

When detecting the wood panel target, five IP67 sensors showed reasonable accuracy, with RMS errors ranging from 0.26 to 6.91 cm (Table 7). For three irregularly shaped, simulated canopy targets, range of detection RMS error results were from 4.18 to 12.77 cm. During tests with the simulated canopy, the sensors consistently underestimated the target distances (Fig. 10). This might have been due to relatively high air temperature (29 °C), that influenced the speed of sound similar to the effects experienced in the air temperature tests. This underestimation of distance to the foliage might cause canopy volume overestimation (Giles et al., 1988). Inaccurate detection of canopy volume would cause targets to be over or under sprayed. For example, our test results showed that the IP67 sensing system might cause spray rate variations from 9.3 to 135% of desired application rates (based on following parameters: canopy detecting interval of 50 ms, travel speed from 0.45 to 1.34 m/s, maximum canopy distance of 60.96 cm, minimum canopy distance of 30.48 cm, sensor to tree row centerline distance of 60.96 cm, and application rate of 93.8 mL/m^3). It should be noted that the maximum variation occurred when the target volume was relatively small (16.3% of the maximum volume). The variation in the application rate could be reduced to 0.2–35% of desired application rates by careful calibration to determine proper offsets for detection distances.

4. Summary and conclusions

The durability and measurement stability of an ultrasonic sensor were investigated under simulated field conditions. In addition, potential issues in detecting a target with multiple synchronized sensors were investigated by integrating them into a prototype sprayer. Although the sensor showed an inherent issue in distance measurement accuracy when the spray liquid deposited on the transducer, the error could be minimized by optimizing the sensor/nozzle relative mounting locations on a sprayer.

Specific conclusions from this study were as follows:

(1) Exposure to outdoor cold weather conditions for 40 days did not significantly change the function and accuracy of the ultrasonic sensor; the mean RMS error of detection distances increased from 3.31 to 3.55 cm.
(2) Wind speeds over the range from 1.5 to 7.5 m/s did not have a significant effect on sensor measurements.
(3) The presence of a dust cloud in the line-of-sight of the sensor did not have a significant influence on sensor detected distances.
(4) Mean RMS errors of the sensor ranged from 10.1 to 19.4 cm when artificial plant targets were 81.9-cm away and sprayer travel speed ranged from 0.8 to 3.0 m/s. Utilizing a derivative filter to avoid obviously erroneous data samples improved the measurement accuracy by reducing RMS errors to 6.4–7.9 cm.
(5) The accuracy of the sensor was affected by air temperature. The mean RMS error of the sensor measurements increased to 2.2 cm at the temperature from 19 to 35 °C, and 4.6 cm at the temperature above 35 °C. The result demonstrated that the sensor had sufficient accuracy within the ambient temperature range (19–35 °C) for the field sprayer operation by achieving a low mean RMS error.
(6) The mean RMS error of the sensor measurements ranged from 2.3 to 83.0 cm for the spray cloud test. It was identified that the spatial configurations between the sensor and spray nozzle significantly influenced the detection performance of the sensor. Spray liquid deposition on the transducer of an ultrasonic sensor by spray clouds should be minimized by proper spacing between the nozzles and the sensors when mounted on field sprayers.
(7) Isolating the pathway for ultrasonic wave of the sensor was desirable to avoid interference between sensors when synchronized multiple ultrasonic sensors were operated.

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